1710

Discussion Papers

Deutsches Institut für Wirtschaftsforschung 2017

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Olga Chiappinelli and Karsten Neuhoff

IMPRESSUM

DIW Berlin
German Institute for Economic Research
Mohrenstr. 58
10117 Berlin

Tel. +49 (30) 897 89-0
Fax +49 (30) 897 89-200
http://www.diw.de

ISSN electronic edition 1619-4535

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Time-consistent carbon pricing*

Olga Chiappinelli[†] and Karsten Neuhoff[‡]

December 20, 2017

Abstract

In this paper we show that carbon pricing is subject to time-inconsistency and we investigate solutions to improve on the problem and restore the incentive for the private sector to invest in low-carbon innovation. We show that a superior price-investment equilibrium can be sustained in the long-term, if the policy-maker is enough forward looking and allowed to build reputation. In the short-term, time-inconsistency can be alleviated by complementing carbon pricing with project-based carbon price guarantees.

*We thank Joern Richstein, Nils May, Toke Aidt and participants to the 1st Workshop on Economic Theories and Low-Carbon Transformation Policies and the FSR Climate Annual Conference for useful comments. We are grateful for financial support from the German Federal Ministry for Economic Affairs and Energy under grant number 03MAP316. The views and opinions expressed in this publication do not necessarily reflect the views of the Ministry.

[†]DIW Berlin. E-mail: ochiappinelli@diw.de.

[‡]DIW Berlin. E-mail: KNeuhoff@diw.de.

1 Introduction

In order to meet the ambitious de-carbonization targets we committed to in Paris agreements, radical low-carbon innovation in the emission intensive sectors (e.g., materials) is needed (See e.g., Neuhoff et al (2017) and references therein).

To induce the private sector to invest in radical green innovation of products and processes, governments should set a carbon price sufficiently high to ensure the profitability of such transition. However, carbon pricing is prone to time inconsistency and credibility problems. These arise for mainly two reasons. First, there are multiple and conflicting objectives in the political and regulatory agendas: long-term aimed carbon-reduction policies conflict with short-term social and economic objectives, such as distributional implications of higher carbon price, and public finance constraints. This multi-objective nature of the government social welfare function creates a trade-off between climate and redistributive goals and governments are typically biased towards the short-term side of this trade-off, both because of electoral concerns and political alternation.

The second reason is that the firm and the government take sequential moves, and low-carbon investments are irreversible and specific in nature. The two arguments lead to an ex-post opportunism problem: the former creates *motivation* for ex-post opportunism, while the latter creates the *scope*. The government has an incentive to create expectations of a relatively high carbon price (e.g., announce the emission of a small number of permits or of a high carbon tax) in order to induce the firm to invest in radical green innovation (hence achieving the goal of reducing emissions); then, after the firm has sunk the investment costs, the government has an incentive to ex-post lower the carbon price in order to avoid the negative impact on consumer surplus. However, as rational agents, potential innovators anticipate the risk of such ex-post opportunistic behavior on the side of the government, and do not invest in the first place, so that no emission reduction is realized.

This time inconsistency problem is not new to the economic literature and not specific to climate policy, but common to many regulatory settings, such as monetary policy (see e.g., Barro (1983) and Kydland and Prescott (1977)) and rate-of-return regulation (see e.g, Laffont and Tirole (1993)). Some past research has studied the problem in the specific context of climate policy, suggesting a number of solutions: tax earmarking (e.g., Marsiliani and Renstrm (2000), delegation of environmental regulation to an independent environmental agency (e.g., Helm et al. (2003) and Helm et al. (2004)), investment subsidies (e.g., Abrego and Perroni (2002), Golombeck et al. (2010), Montero (2011), pollution taxes (e.g., Biglaiser et al. (1995)), options to pollute and procurement (e.g., Laffont and Tirole (1996)).

Differently from the above mentioned literature, which takes the time-inonsistency problem for granted, we assume that policy makers are not totally present-biased and have some degree of forward lookingness. In this context, allowing for reputation effects (which can emerge in a repeated relationship) can bring some improvements. This exercise was done in the regulatory context (see e.g., Salant and Woroch (1991), Salant and Woroch (1992)),Gilbert and Newbery (1994) and Martimort (2006)) but never specific to the climate policy case. Therefore, the first contribution of this paper is to investigate whether a repeated relationship between the private sector and the government can alleviate the problem of time-inconsistency and hold up underlying carbon pricing policies.

We show the time-inconsistency problem in a simple model of carbon pricing and we find that reputational forces can bring some improvement on the committment problem in the long run and partially restore the incentive for the private sector to invest. The equilibrium carbon price and the level of investment are distorted downward with respect to the commitment benchmark, so to ensure that the benefits of investment (in terms of reduced emissions) are spread over time, therefore increasing the opportunity cost for the goverment of forgoing the relationship with the firm.

The second contribution of the paper is to investigate whether integrating the carbon price with additional policies can improve on the time-inconsistency problem in the short term. In particular we consider the role of project-based carbon-price guarantees, where a carbon price is guaranteed for a share of the project (see e.g., Helm and Hepburn (2005)). In this case the time-inconsistency problem is expected to be less severe since the government can renege on the announced price only on part of the project.

As far as we know we are the first in providing a formal modelization of carbon contracts. We find that carbon contracts alleviate the time-inconsistency problem and partially restore the incentive for the firm to invest, relative to the static outcome with no policies. Also an interesting comparative statics result emerge, namely that depending on the extent of the guarantee, both the optimal level of investment and the optimal carbon price are non monotonic in the guaranteed price. When the size of the guarantee is high (low) enough the optimal investment increases (decreases) in the guaranteed price. On the other hand, for high (low) coverages, the optimal carbon price decreases (increases) with the carbon price. The intuition for the latter is that when the coverage is high, it is too costly for the government to pay the price differential.

The structure of the paper is as follows. In Section 2 we present a simple model of carbon pricing. In Section 3 we characterize the optimal carbon pricing in the short-term. In Section 4 we consider a repeated pricing game and characterize optimal long-term pricing. In Section 5 we consider the case where carbon price is complemented with carbon contracts. In Section 6 we briefly conclude. All proofs are gathered in the Appendix.

2 The model

Consider the follwing simple setting of pricing regulation similar to Laffont and Tirole (1996). There is a continuum of agents/potential polluters with demand for a polluting good (e.g., steel, energy) $Q(p)$, $Q' < 0$ where p is the carbon price as reflected in the good price (we assume full carbon pass through). The carbon price is "set" by the government, in the sense that the governemnt can influence the carbon price via setting the number of allowances or a carbon tax. For simplicity, we assume that there is a single firm producing the good at no cost and meeting all demand[1].

The production of the good produces emissions linearly: $E = eQ(p)$, where $e > 0$ is a dirtiness parameter. Emissions can be reduced if the firm invests in a cleaner technology: a level of investment x reduces emissions for $e(Q(p) - x)$, costs $C(x)$ to the innovator ($C(0) = 0$, $C'(0) = 0$, and $C' > 0$, $C'' > 0$ for $x > 0$ and yields revenues $R(x) = xpQ(p)$ (investment increases revenues proportionally). In the following we will assume convex technology for the firm $C(x) = c\frac{x^2}{2}$, $c > 0$.[2] There is complete information in the model, and both the government and the firm are risk-neutral.

The timing of the game is as follows:

t=0 The government announces a carbon price

t=1 The firm makes an investment decision

t=2 The government implements the price and demand realizes

The government is Nash leader in this setting and the firm Nash follower. Given the sequentiality of the moves between the government and the firm, there is scope for ex-post opportunism on the side of the government: the government can ex-post change the price by manipulating the number of allowances or change the tax rate.

[1]Since we want to focus on the innovation investment decision, production is not a decision variable for the firm)

[2]In this model we disregard the technology frontier and the trade-off between cleaner technology and production cost.

According to the setting above, the objecive function of government is as follows:

$$W = \int_{p}^{\overline{p}} Q(z)dz - e[Q(p) - x] \tag{1}$$

The government only cares about consumers welfare (gives zero weight to the firm profits). The first term is the consumers surplus from consumption of the good, which falls with the price-raising effects of the carbon price. The second term is the damage from emissions, which also falls the higher is the price. Therefore the objective function above represents in a straightforward way the trade-off underlying carbon pricing, which on one hand decreses welfare through a decrease in consumer welfare but on the other hand increases welfare through a decrease in the damage from emissions. [3]

The profit function of the firm is as follows:

$$\Pi = (1 + x)pQ(p) - \frac{cx^2}{2} \tag{2}$$

Profits from innovation depend on the level of innovation. Clearly, by setting the carbon price, the government determines the profitability for the firm from investment.

3 Optimal carbon pricing

3.1 Commitment benchmark

Assume that there is a third party or institution that can take the government accountable for climate policy. In this case the government would have to stick to the announced price after the firm has invested in innovation. Therefore the problem of the government would be to choose a carbon price that maximizes his objective function while taking into account the reaction function of the firm to the announced price $x(p)$.

That is, the problem of the government is as follows:

$$\max_{p} \int_{p}^{\overline{p}} Q(z)dz - e[Q(p) - x(p)] \tag{3}$$

where: $x(p) = \frac{pQ(p)}{c}$

[3] We abstract from revenue considerations (there are no revenues from carbon taxes or selling of allowances). The only benefit of carbon price is through the reduction of emissions due to increased investment.

The reaction function the potential innovator to the announced price is $x(p)$ is the level of investment which balances marginal benefit of investing in terms of marginal increase of profitability $(pQ(p))$ and its cost (cx).
In this case the first best solution can be implemented:

$$p^{FB}: \quad Q(p) = \frac{e}{c}[Q(p) + pQ'(p)] - eQ'(p) \tag{4}$$

where the first-best price balances the marginal cost (LHS) of a price increse in terms of reduction in consumer surplus $(Q(p))$ and marginal benefit (RHS) in terms of reduction of emissions, both trough increased investment (first term) and in terms of reduced consumption. As expected, the FB price is an increasing function of the dirtiness of the technology $(\frac{\partial p^{FB}}{\partial e} > 0)$ - the higher the dirtiness the higher the price needed at the margin to decrease emissions - and a decreasing function of the investment cost $(\frac{\partial p^{FB}}{\partial c} > 0)$ - the higher the technological cost the higher the price needed to the firm as incentive to invest.

The resulting equilibrium investment level would therefore be:

$$x^{FB} = \frac{p^{FB}Q(p^{FB})}{c} \tag{5}$$

3.2 No committment

Since there is in principle no reason to believe that the government will be able to commit to the announced price, the government will choose the ex-post optimal price, given the firm investment:

$$\max_p \int_p^{\overline{p}} Q(z)dz - e[Q(p) - x] \tag{6}$$

It is straightforward to check that for any level of investment chosen by the firm, the government always find it optimal to set a zero carbon price (since the government can ex post reduce the cost for consumers of inducing the potential innovator to invest). Anticipating this behavior in his investment decision, the firm will always choose not to invest, so that in the equilibrium of the no commitment case there will always be zero carbon price $(p^* = 0)$ and zero investment $(x^* = x(p^*) = 0)$. This result follows the standard expropriation argument of the regulation literature (See e.g., Williamson (1975) and Laffont and Tirole (1993)).

4 Repeated pricing game

The assumption, as adopted by the literature on time-inconsistency - that the government is completely present-biased and that therefore the relationship between the government and the regulator is a static one, is rather extreme. In fact, the government and the private sector are in a long(er)-term relationship. Therefore, it is interesting and relevant to investigate how the results change when we allow the government and the firm to interact in a multi-period setting where the government can develop some reputation for good behavior and the firm can observe the behavior of government in the past and behave consequently (use past behavior of the government as proxy for present behavior).

Therefore in the following we assume that the government and the firm are in an indefinitely long relationship. The static game is repeated for infinite periods. [4]. Government and firm have the same discount factor $\delta \in [0, 1]$.

What we ask is whether a more cooperative outcome than the static game ($p > p^*$, $x > x^*$) can be sustained as a trigger strategies Subgame Perfect Nash Equilibrium (SPNE). That is simply the fact that now the firm can observe the behavior of the government in past periods and punish him accordingly can be enough to induce the government to stick to its announcements, and enough to have an improvement relative to the static negative outcome[5].

Trigger strategies prescribe to each part to behave as long as the other party behaves (remain on the equilibrium path) and return to the static equilibrium NE as soon as someone deviates. In this context trigger strategies are as follows:

- If the government deviates from announced p at any date, the firm will not invest anymore at any future date
- If the firm deviates from investing x at any date, the government will implement a 0 price at any future date

The trigger strategy for the firm is that the firm invests in the first period trusting the announcement of the government (giving the government the benefit of the doubt) and keeps investing as long as the government respects announcements. As soon as the government reneges on the announcement the firm punish the government forever by not investing anymore. The trigger strategy for the government is to set carbon price as

[4]There is no dynamics in the model, demand and investment are unchanging over periods. Interpretation: investment costs are sunk in every period

[5]Similar analysis were done by **?** and , but in a general regulation context

long as the firm invests and 0 forever as soon as the firm does not invest (As it will be straightforward, as a Stackelberg follower the firm will never deviate in this context).

Below we formally define trigger strategies and equilibrium candidate profile (p, x). Strategies are rules that determine actions at each date as functions of the history up to that time. The history of the game up to period t is $h_t = (x_0, p_0, x_1, p_1, ..., x_{t-1}, p_{t-1})$. A strategy for the government is a sequence of functions $g = \{g_t\}$ specifying a carbon price in each period t as a function of the history $g_t = h_t \to p_t$. A strategy for the firm is a sequence of functions $f = \{f_t\}$ specifying an investment level for each t as a function of the history $f_t = h_t \to x_t$.

In order to assess whether the profile (p, x) can be sustained as a trigger strategy equilibrium, we need to check that there are no profitable deviations from any of the two players.

We first need to calculate the deviation payoffs for the government, that is when the firm invests believing the announcement of the government and then the government sets a zero price. The outcome in that case would be $p^D = 0$ $x^D = x$ and the government payoff:

$$\int_0^{\overline{p}} Q(z)dz - e[Q(0) - x] \tag{7}$$

The government get investment and emissions reduction at no cost (in terms of consumer surplus loss).

The per-period punishment payoff will be:

$$\int_0^{\overline{p}} Q(z)dz - eQ(p) \tag{8}$$

The no-deviation condition for the government requires comparing the long-term payoff of conforming

$$\sum_{t=0}^{\infty} \delta^t \left[\int_p^{\overline{p}} Q(z)dz - e[Q(p) - x] \right] \tag{9}$$

and the long-term payoff of deviating (in the first period, since it is optimal for the government to deviate as soon as possible)

$$\int_0^{\overline{p}} Q(z)dz - e[Q(0) - x] + \sum_{t=1}^{\infty} \delta^t \left[\int_0^{\overline{p}} Q(z)dz - eQ(p) \right] \tag{10}$$

which leads to the following per-period no-deviation condition

$$\delta x e \geq \int_0^p Q(z)d(z) - [Q(0) - Q(p)]e \tag{11}$$

That is the government in any given period compares the benefit from not deviating, in terms of discounted reduction of emissions due to new investment, and the benefit from deviating, in terms of an increase in consumer surplus due to a lower price net of the per-period increase in emissions due to increased consumption.[6].

As standard in repeated games, the good outcome can be sustained only if the short term gain from deviating is smaller than long term gain from conforming. This happens if the goverment is enough forward looking.

The no-deviation condition for the firm is as follows:

$$(1+x)pQ(p) - c\frac{x^2}{2} \geq 0 \tag{12}$$

And it is going to hold trivially when the one of the government holds. The following proposition characterizes the solutions of the repeated pricing games

Proposition 1.

- *If $\delta \to 1$, the first-best solution can be implemented*

$$p^{FB}: \quad \frac{e}{c} = \frac{Q(p) + eQ'(p)}{Q(p) + pQ'(p)} \tag{13}$$

- *For lower values of δ, government's incentive constraint is binding*

$$p^{SB}: \quad \frac{e\delta}{c} = \frac{Q(p) + eQ'(p)}{Q(p) + pQ'(p)} \tag{14}$$

such that $p^{SB} < p^{FB} \to x^{SB} < x^{FB}$

The proof is analogous to the one in Martimort (2006), so we skip it here. The result that $p^{SB} < p^{FB} \to x^{SB} < x^{FB}$ is straightforward from noticing that RHS of (13) and(14) is increasing in p.

The interpretation of Proposition 1 is as follows: when the discount factor is high enough the government's incentive constraint/no-dev condition is slack since the government's objective function is strictly positive at the first-best. When the discount factor is lower, the condition does not hold anymore at the first best, and therefore a lower price

[6]We also have to check the histories when the government cheated, and check whether the firm has an incentive to punish the government in all the following periods. If it conforms and does not invest it will get zero profits, while if it deviates by investing a positive level of resources it will incur a loss Π^D

is needed to have the condition hold again. The intutition for the downward distortion is that lowering the price spreads the benefit from investment, increasing the opportunity cost from forgoing the relationship.

5 Project-based carbon contracts

In this section we investigate whether integrating the carbon price with carbon contracts improves on the time-consistency problem and in restoring the incentive for the private sector to invest.

In project-based carbon contracts, firm and the government sign a credible contract where the firm is guaranteed a price p_G for a share k of the investment.[7].

We consider the case that carbon contracts are implemented as contracts for differences[8]. That is, if the carbon price is lower than the contracted guaranteed price $p < p_G$, the government pays $(p_G - p)kx$ to the firm, while if the carbon price turns out to be higher than the guaranteed price $p > p_G$, the firm pays $(p - p_G)kx$ to the government.

Let kx be the share of the project covered by the price guarantee, while $(1-k)x$ is the unprotected part ($k \in (0,1)$). An alternative interpretation for k is the share of the sector where carbon contracts are feasible. While can do that for mitigation of processes (e.g., steel plants), feasibility looks much more limited in the case of products (e.g., car-makers), where transaction costs could be proibitive (e.g., it would be much more complicated to define the benchmark, in the example of contracts for differences).

The timing of the game is as follows:

t=0 The government announces a carbon price p and signs a binding carbon contract with the firm where p_G is guaranteed for share k of investment

t=1 The firm makes an investment decision

t=2 The government implements the carbon price and payments are made

Given the prices p^G, and p chosen by the government, the firm now maximizes

$$\Pi_{cc} = (1+x)pQ(p) + (p_G - p)kx - c\frac{x^2}{2} \tag{15}$$

[7]Project-based carbon contracts have been very recently introduced in the United Kingdom for the power sector and are now in the design stage for industry (See Helm and Hepburn (2005) for an assessment)

[8]This is one of the main implementation option under consideration in the current design.

which leads to the following reaction function

$$x(p^G, p) = x(p, p_G) = \frac{pQ(p) + k(p_G - p)}{c} \tag{16}$$

It is straightforward to see that even if the government were to set a zero carbon price, the firm would still have an incentive to invest a positive level. Therefore carbon contracts can restore the incentive for investment in the absence of commitment.

However the government will never set a zero carbon price because now there is a cost in doing so. By backward induction, the government will set a carbon price $p(p_G)$ that maximizes:

$$W_{cc} = \int_p^{\overline{p}} Q(z)dz - e[Q(p) - x] - (p_G - p)kx \tag{17}$$

From which we have that the equilibrium levels of carbon price and investment as a function of the guaranteed price are characterized by the following conditions:

$$p(p_G) : \frac{Q(p) + Q'(p)e}{z} = \frac{Q(p)p + z(p_G - p)}{c} \tag{18}$$

$$x(p(p_G), p_G) = \frac{p(p_G)Q(p(p_G)) + z(p_G - p(p_G))}{c} \tag{19}$$

Before characterizing the optimal choice of the carbon price, it is interesting to notice the following:

Proposition 2. *The effect of an increase in the guaranteed price on the optimal investment level of the firm can be decomposed as follows:*

$$\frac{dx(p(p_G), p_G)}{dp_G} = \underbrace{\frac{\partial x(p(p_G), p_G)}{\partial p}\frac{\partial p(p_G)}{\partial p_G}}_{\textit{Indirect Effect}} + \underbrace{\frac{\partial x(p(p_G), p_G)}{\partial p_G}}_{\textit{Direct Effect}} \tag{20}$$

- *A indirect effect:*

$$\frac{\partial x(p(p_G), p_G)}{\partial p}\frac{\partial p(p_G)}{\partial p_G} \leq 0 \tag{21}$$

- *A direct effect:*

$$\frac{\partial x(p(p_G), p_G)}{\partial p_G} > 0. \tag{22}$$

The intuition of Proposition 2 is as follows. In the presence of price guarantees, an increase in carbon price has less straightforward implications for optimal investment than in the case without: on one hand it increases the profitability of the investment, which induces higher investment, but on the other hand it reduces the payment that the firm gets from the government, which reduces optimal investment. Which effect dominates depends on the size of the guarantee. If k is high enough, the firm cares more about the missed payment than the higher profitability and therefore $\frac{\partial x(p(p_G),p_G)}{\partial p} < 0$. If k is lower, the opposite holds $\frac{\partial x(p(p_G),p_G)}{\partial p} \geq 0$.

As for the impact of price guarantee on optimal price $\frac{\partial p(p_G)}{\partial p_G}$: if the size of guarantee is low enough, an increase in the guaranteed price makes the optimal carbon price increase, because it is not too costly for the government to pay the difference between prices. If instead the coverage is very generous it is costly for the government to pay the difference between prices, and therefore the optimal carbon price decreases for higher guaranteed prices.

Since the size of the guarantee has opposite effects on the two components of the indirect effect, the indirect effect is always negative. On the other hand, the direct effect of an increase in the guaranteed price on optimal investment is always positive.

It is possible to show that each effect can dominate as follows:

Lemma 1. *The indirect negative effect dominates for small enough size of the guarantee, while the positive direct effect dominates for high size of the guarantee*

Therefore, the optimal level of investment of the firm will increase positively with respect of the guaranteed price if the coverage of the guarantee is high enough.

Last step by backward induction is to characterize the optimal choice of guaranteed price by the government. The government will chose p_G that solves:

$$int_{p(p_G)}^{\overline{p}} Q(z)dz - Q(p(p_G))e + x(p(p_G), p_G)[e - (p_G - p(p_G)k)] \tag{23}$$

Proposition 3. *The optimal choice of guaranteed price for the government solves*

$$\begin{aligned}
&- Q(p(p_G))\frac{\partial p(p_G)}{\partial p_G} + e\left[-Q'(p(p_G))\frac{\partial p(p_G)}{\partial p_G} + \frac{\partial x(p(p_G), p_G)}{\partial p}\frac{\partial p(p_G)}{\partial p_G} + \frac{\partial x(p(p_G), p_G)}{\partial p_G}\right] \\
&-\left\{\frac{\partial x(p(p_G), p_G)}{\partial p}\frac{\partial p(p_G)}{\partial p_G} + \frac{\partial x(p(p_G), p_G)}{\partial p_G}](p_G - p(p_G)) + x(p(p_G), p_G)(1 - \frac{\partial p(p_G)}{\partial p_G})z\right\} = 0
\end{aligned} \tag{24}$$

Where the first term is the marginal impact on consumer surplus, the second (squared brackets) the net impact on emissions, and the third (curly brackets) the net impact on finances (in terms of the price difference to pay to the firm)

The government's optimal choice of guaranteed price equates the marginal benefit (LHS) from the guaranteed price to its marginal cost (RHS). As it is possible to check these are different depending on the sign of $\frac{dp(p_G)}{dp_G}$, which in turns, as shown before, depends on the size of the guarantee, k.
In particular, when k is low enough ($\frac{\partial p(p_G)}{\partial p_G} > 0$), the marginal cost (LHS) and the marginal benefit (RHS) are as follows:

$$Q(p(p_G))\frac{\partial p(p_G)}{\partial p_G} + \left[\frac{\partial x(p(p_G),p_G)}{\partial p}\frac{\partial p(p_G)}{\partial p_G} + \frac{\partial x(p(p_G),p_G)}{\partial p_G}](p_G - p(p_G))\right]$$
$$x(p(p_G),p_G)(1-\frac{\partial p(p_G)}{\partial p_G})z = -eQ'(p(p_G))\frac{\partial p(p_G)}{\partial p_G} + e\left[\frac{\partial x(p(p_G),p_G)}{\partial p}\frac{\partial p(p_G)}{\partial p_G} + \frac{\partial x(p(p_G),p_G)}{\partial p_G}\right] \tag{25}$$

The three components of the marginal cost are resp. i) marginal decrease in consumer surplus due to higher carbon price, ii) marginal extra payment of price difference to pay to the firm because of extra investment, iii) marginal extra payment due to larger price difference. The two components of marginal benefit are resp. i) marginal reduction in emissions due to reduced consumption, ii) marginal reduction in emissions due to higher investment When k is high enough ($\frac{\partial p(p_G)}{\partial p_G} < 0$) the interpretation is the opposite. The LHS of 25 now represents the marginal benefit and the RHS the marginal cost. The three components of the marginal benefit are resp. i) marginal increase in consumer surplus due to higher price, ii) marginal saving in terms of price difference due to lower investment, iii) marginal savings in payment due to smaller price difference. The components of marginal cost are resp. i) marginal cost in terms of higher emissions due to higher consumption, ii) marginal increase in emissions due to lower investment

6 Conclusion

In this paper we have provided a novel theoretical analysis of the problem of time-inconsistency in carbon pricing, and its effect on the incentives for the private sector to invest in radical green innovation.

We have investigated whether a repeated relationship between the private sector and the government can alleviate the problem of time-inconsistency and hold up underlying carbon pricing policies. We have shown the time-inconsistency problem in a simple model of carbon pricing and found that reputational forces can bring some improvement on the committment problem and partially restore the incentive for the private sector to invest. The equilibrium carbon price and the level of investment are distorted downward with respect to the commitment benchmark, so to ensure that the benefits of investment (in terms of reduced emissions) are spread over time, therefore increasing the opportunity cost for the goverment of forgoing the relationship with the firm.

Furthermore, we have investigated whether integrating carbon pricing with additional policies can improve on the time-inconsistency problem in the short term. In particular we considerd the role of project-based carbon-price guarantees. where a carbon price is guaranteed for a share of the project. In this case the time-inconsistency problem is expected to be less severe since the government can renege on the announced price only on part of the project. As far as we know we are the first in providing a formal modelization of carbon contracts. We found that carbon contracts alleviate the time-inconsistency problem and partially restore the incentive for the firm to invest. Also an interesting comparative statics result emerged, namely that depending on the extent of the guarantee, both the optimal level of investment and the optimal carbon price are non monotonic in the guaranteed price. When the size of the guarantee is high (low) enougj the optimal investment increases (decreases) in the guaranteed price. On the other hand, for high (low) coverages, the optimal carbon price decreases (increases) with the carbon price. The intuition for the latter is that when the coverage is high, it is too costly for the government to pay the price differential. This work can be extended in many directions, including the following. First, the model can be made more realistic by allowing for technological frontier, competition effects, firm risk-aversion, information asymmetries and dynamics to have a role. Second, the role of other policies can be investigated. In particular, we plan to consider the public co-funding of investment in innovative projects.

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Appendix

6.1 Proof of Proposition 2

The indirect effect is made of two components

$$\frac{\partial x(p(p_G), p_G)}{\partial p} = \frac{Q(p) + pQ'(p) - k}{c} \tag{26}$$

$$\frac{\partial p(p_G)}{\partial p_G} = -\frac{F_{p_G}}{F_p} \tag{27}$$

where

$$F = \frac{Q(p) + Q'(p)e}{k} - \frac{pQ(p) + k(p_G - p)}{c} \tag{28}$$

$$F_{p_G} = \frac{\partial F}{\partial p_G} = -\frac{k}{c} \tag{29}$$

$$F_p = \frac{\partial F}{\partial p} = \frac{c[Q'(p) + Q''(p)e] - k[Q(p) + pQ'(p) - k]}{kc} \tag{30}$$

The first component is positive if $k \leq Q(p) + pQ'(p)$ and negative otherwise.

Given that F_{p_G} is negative, the sign of the second component $\frac{\partial p(p_G)}{\partial p_G}$ is determined by the sign of F_p.
It is possible to prove the following:

Lemma 2. *$F_p < 0$ for k low enough, which implies $\frac{\partial p(p_G)}{\partial p_G} < 0$ and $F_p > 0$ for k high enough, which implies $\frac{\partial p(p_G)}{\partial p_G} > 0$.*

Proof.
$F_p > 0$ iff

$$\frac{[Q'(p) + Q''(p)e]}{k} > [Q(p) + pQ'(p) - k] \tag{31}$$

Consider the following: $\frac{\partial RHS}{\partial k} = -1$, $\frac{\partial LHS}{\partial k} = \frac{k - c[Q'(p) + Q''(p)e]}{k^2}$. Two cases are possible:

- If e is small enough, $Q'(p) + Q''(p)e < 0$ and $\frac{\partial LHS}{\partial k} > 0$, then $RHS > LHS$, and therefore $F_p < 0$, for low enough levels of k, while $RHS < LHS$, and therefore $F_p > 0$, for high enough levels of k

- If e is high enough, $Q'(p) + Q''(p)e > 0$. Therefore $\frac{\partial LHS}{\partial k} > 0$ for $k > \overline{k}$, where $\overline{k} = c[Q'(p) + Q''(p)e]$ and negative othwerwise. In the first case, then, as before RHS¿LHS, and therefore $F_p < 0$, for low enough levels of k, while RHS¡LHS , and therefore $F_p > 0$, for high enough levels of k ($k > \overline{k}$)[9].

Q.V.D.
Therefore we can conclude that if k is low enough $\frac{\partial x(p(p_G),p_G)}{\partial p} > 0$ and $\frac{\partial p(p_G)}{\partial p_G} < 0$, so the indirect effect is negative. If k high enough, $\frac{\partial x(p(p_G),p_G)}{\partial p} < 0$ and $\frac{\partial p(p_G)}{\partial p_G} > 0$, and the total indirect effect is negative again.
The direct effect is always positive

$$\frac{\partial x(p(p_G), p_G)}{\partial p_G} = \frac{k}{c} > 0. \tag{32}$$

6.2 Proof of Lemma 1

Given expressions for the direct and indirect effects respectively as follows:

$$\frac{\partial x(p(p_G), p_G)}{\partial p_G} = \frac{k}{c} \tag{33}$$

$$\frac{\partial x(p(p_G), p_G)}{\partial p}\frac{\partial p(p_G)}{\partial p_G} = \frac{Q(p) + pQ'(p) - k}{c}\frac{k^2}{c[Q'(p) + Q''(p)e] - z[Q(p) + pQ'(p) - z]} \tag{34}$$

The direct effect will be larger than the indirect effect iff

$$c[Q'(p) + Q''(p)e] > 2k[Q(p) + pQ'(p) - k] \tag{35}$$

which for analogous reasoning as in the proof of Proposition 2 will be true if z is high enough, otherwise the indirect effect will dominate

[9]Notice that for linear demand the sign does not depend on e